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Short Title: Targeted Herbicide Programs

Row Middle Herbicide Programs for Plasticulture Vegetables Using Targeted Herbicide Applications

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ABSTRACT

In plasticulture production, smart spray technology can detect weeds and apply herbicides only where needed in the area between raised, plastic-covered beds (row middle). This technology has the potential to reduce herbicide use and lower input costs. A prototype smart spray system was developed at the Gulf Coast Research and Education Center (GCREC) in Wimauma, FL, that utilizes YOLO-V3 convolutional neural networks to differentiate broadleaf, grass, and nutsedge weeds in row middles. Two sets of field experiments were conducted to determine the efficacy of smart spray technology using a combination of preemergence (PRE) and postemergence (POST) herbicides. All treatments reduced weed density, and targeted applications were as effective as banded treatments. Overall, including a PRE herbicide tended to lower weed density compared to POST applications alone, regardless of application technique. Two banded PRE herbicide applications and two targeted POST applications reduced herbicide use by 52% and 13% compared to banded PRE and POST applications in Experiments 1 and 2, respectively. The reduction from two to one PRE-herbicide applications did not result in an overall herbicide use or cost reduction in Experiment 1, as the decrease in PRE herbicides resulted in increased POST-herbicide usage. In the absence of a banded PRE application, targeted compared to banded POST applications, herbicide usage was reduced by 40 to 67% in Experiment 1 and 79 to 84% in Experiment 2. Smart spray technology is an effective weed management tool for row middles in plasticulture production systems with or without PRE-herbicide applications.

Keywords: Targeted spray, weed control, vegetables, paraquat, glufosinate

Introduction

The plasticulture system involves plastic mulches, drip irrigation, and soil fumigation. It is widely adopted among specialty crop growers in the Southeastern USA due to improved yields, increased water and fertilizer use, and reduced weed pressure (Freeman and Gnayem 2005; Lamont Jr. 1996). Black polyethylene mulch inhibits sunlight penetration, preventing the germination and growth of most weeds. However, over the season, broadleaf and grass weed emergence can happen in the space between the beds (row middles) and transplant holes punctured in the plastic mulch, which can affect the yield (Buzanini and Boyd 2024), shelter nematodes (AbdelRazeK et al. 2023), and diseases (Dentika et al. 2021)

The fumigation process consists of volatile chemical compounds applied in the soil prior to planting a crop, commonly used to control soil-borne fungal pathogens, nematodes, and weeds in the plasticulture system (Castellano-Hinojosa et al. 2022). However, no fumigant is applied in row middles, which can contribute to the most challenging weed control. To avoid the direct and indirect effects of weeds emerging in row middles on crop quality and yield, weed control typically relies on preemergence (PRE) and postemergence (POST) emergence herbicides due to their effectiveness, ease of use and low cost compared with other management options such as hand weeding (Dittmar 2013; Fennimore and Doohan 2008). Using technologies to apply herbicides specifically where weeds occur should reduce overall herbicide use.

Weeds in row middles are often managed with PRE herbicides applied shortly after fumigation and before crop transplant, with POST herbicides applied in conjunction with PRE applications or as needed post-transplant during the crop cycle (Sharpe and Boyd 2019). Multiple herbicide applications are typically required to achieve weed season-long control. In addition, mixtures of POST herbicides are often used to broaden the weed control spectrum. Previous research has attempted to identify effective POST mix options (Buzanini et al. 2023; Sharpe et al. 2020) or combinations of PRE and POST herbicides (Boyd 2016; Gilreath et al. 1987) for row middles. However, very few publications examine row middle weed management with herbicides, and most of the research was conducted in Florida.

Flumioxazin is a N-phenyl phthalimide herbicide with excellent efficacy that has an inhibitory effect on the protoporphyrinogen oxidase (PPO) enzyme in a wide range of weed species (Iwashita et al. 2022; Price et al. 2004)). It is widely used in row middles and has both

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soil surface residual and foliar contact properties (Iwashita et al. 2022). Tank mixes of PRE herbicides with different action modes can broaden the weed control spectrum and enhance overall efficacy. For example, Boyd (2016) reported that weed control in vegetable row middles increased from 42 to 73% with *S*-metolachlor and flumioxazin applied separately to 91% when both modes of action were applied in a tank mixture (Boyd 2016).

Glufosinate is a non-selective, POST herbicide recently registered for fruiting vegetable row middles. It was previously used primarily in non-crop areas or glufosinate-resistant agronomic crops for postemergence and pre-plant burndown (Dayan et al. 2019). Mixing different herbicides in a tank is often necessary to control broadleaf, grass, and nutsedge in row middles. This approach broadens the range of weeds that can be controlled and reduces the overall cost of application compared to using the herbicides separately (Kammler et al. 2010).

In most cases, herbicides are applied to row middles using shielded applicators that band the herbicides between the raised beds. Herbicides are sprayed across the entire middle area of the row, even though weeds typically emerge in non-uniform patterns. Applying herbicides only where weeds occur would reduce herbicide use and input costs and minimize unnecessary environmental pesticide inputs. Object detection based on Convolutional Neural Networks (CNN) has shown significant potential in detecting weeds and saving herbicides in comparison to other applications (Etienne et al. 2021; Epée Missé 2020; Lati et al. 2021; Partel et al. 2019; Buzanini et al. 2023). CNNs are subjected to supervised training using labeled image datasets to build robust models to identify desired objects (Sharpe et al. 2020). CNNs, like YOLO (You Only Look Once), can classify different categories of objects (Liu and Wang 2020), which is an important aspect required for weed detection. Previous research has proven that targeted spray technology is viable for POST herbicides in row middles (Buzanini et al. 2023). Still, there is a need to determine how this technology could optimally be integrated into an overall spray program over the vegetable season in the plasticulture system.

This research aimed to evaluate the efficacy and costs of PRE and POST herbicide combinations in row middles when applied with conventional or targeted spray technology. In Experiment 1, it was hypothesized that herbicide savings with targeted application technology would be more significant in the presence of PRE herbicides, and the better the control achieved with PRE herbicides, the greater the herbicide savings achieved with targeted POST applications. In

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Experiment 2, the hypothesis was that herbicide savings and weed control could be improved by mixing PRE herbicides.

Materials and Methods

Application Technology

A smart spray system with machine vision developed at the University of Florida (Sharpe et al. 2019) to identify and spray herbicides only where weeds occur was used for all experiments in this paper. The system consists of a digital camera (Logitech (C922x – Pro Stream Webcam -1080p HD camera) Newark, CA) connected to a Linux computer (NVIDIA Jetson Nano, Santa Clara, CA) programmed to capture real-time digital images of the vegetable row middles ahead of two nozzles per row middle. The sprayer boom, attached to a tractor, was 1.85 m long and positioned approximately 0.35 m above the ground. The boom had two sprays 8002EVS nozzles (Teejet Technologies, Wheaton, IL), and the width between them was 0.28 m. The smart spray could spray one row middle per pass. The herbicide treatments were mixed in aluminum spray cans pressurized with CO_2 at 0.24 MPa and connected to the prototype sprayer. The tractor's speed for all applications was 3.4 km h^{-1}.

The study utilized an algorithm (YOLOv3-tiny-3L) that had been pre-trained for weed identification in images with 4035 images and 21467 annotations of weeds on vegetable row middles. The analysis was conducted on a Linux computer developed in 2019 when YOLOv3 was one of the best state-of-the-art object detection models available. The tiny variant of YOLOv3 was selected because it produced sufficient accuracy and high inference speed (frames per second) on the limited compute capacity of NVIDIA Jetson Nano used for the controller, as the full-size YOLOv3 was too slow. As the equipment moves in the field, the image processing software can differentiate between three weed classes: broadleaf, nutsedge, and grass. The model analyses each image and sends triggering information to the corresponding solenoid valve, which opens and closes the spray nozzles when weeds are detected. The system latency factor was 0.254 seconds, used as a look-ahead calculation during a real-time operating system.

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Site description

Two field experiments were conducted in Spring 2020, Fall 2020, and Spring 2021 at the Gulf Coast Research and Education Center (27^{o}N, 82^{o}W) in Balm, FL, to evaluate smart spray technology in plasticulture row middles. The soil at all research sites used for these experiments is a Myakka fine sand. The site for Spring 2020 had a pH of 7.9, 1.26% organic matter, 92.4% sand, 4.8% silt, and 2.8% clay. The site for Fall 2020 and Spring 2021 had a pH of 8.0 and 0.68% organic matter, with the sand, silt, and clay percentages at 92, 5.2, and 2.8%, respectively. Fields were disked and leveled before the experimental setup. Historically, plasticulture crops have grown for several years and are known to have significant nutsedge, grass, and broadleaf weed populations. The beds are 30.5 cm tall, 66 cm wide at the top, and spaced 81 cm apart. They were formed and fumigated with 118 kg ha^{-1} of 56.6% Chloropicrin + 37.1% 1,3-Dichloropropene (Pic-Clor 60 Fumigant; TriEst Ag Group Inc., Greenville, NC) with a standard pre-transplant rig equipped with three back-swept shanks set (20 cm apart) to distribute fumigant throughout the bed uniformly (Kennco Manufacturing Inc, Ruskin, FL). Immediately following fumigation, two drip tape lines with emitters every 30 cm and a flow rate of 1.57 L min^{-1} were buried 2.5 cm beneath the soil surface. The beds were simultaneously covered with a black Totally Impermeable Film (TIF) in the Spring and white TIF in the Fall (Berry Global Films LLC, Sarasota, FL).

No crop was grown in these trials as the focus was on weed management in the row middles, but the field was managed as if a crop was present to ensure realistic field conditions. All experiments were designed as a randomized complete block design (RCBD) with four blocks. PRE and POST herbicide applications (Table 1) occurred after Bed formation (within 14 days of Bed formation following the first flush of weeds in the row middle) and at the time of standard transplant (within the time frame when crops were transplanted in surrounding trials at GCREC). The estimated transplant date fell within the normal range for vegetable production in Central Florida and aligned with activities on commercial farms in the surrounding area.

In all site-years the most common weed species observed included carpetweed (*Mollugo verticillate* L.), threelobe morningglory (*Ipomoea triloba* L.), purple nutsedge (*Cyperus rotundus* L.), common lambsquarters (*Chenopodium album* L.), wild radish (*Raphanus raphanistrum* L.), goosegrass [*Eleusine indica* (L.) Gaertn.], common ragweed (*Ambrosia artemisiifolia* L.), cutleaf

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evening-primrose (*Oenothera laciniata* Hill), Brazil pusley (*Richardia brasiliensis* Gomes) and southern crabgrass [*Digitaria ciliaris* (Retz.) Koeler].

Banded and targeted POST herbicide mixtures applied with 0, 1, or 2 PRE flumioxazin applications (Experiment 1). This experiment aimed to compare targeted POST herbicide tank mixes with 0, 1, or 2-banded PRE flumioxazin applications (Table 2). The primary objective was to determine the most effective way to utilize targeted herbicide application technology within an herbicide program for row middles. It is essential to note that all PRE herbicide applications were banded, whereas POST herbicides were either banded or applied using targeting technology. Treatments (Table 2) were; 1) non-treated control, 2) two banded PRE and POST herbicides applied after bed formation and at standard crop transplant dates (2 PRE fb 2 POST(B)), 3) two banded PRE followed by (fb) two targeted POST applied immediately after bed formation and at standard crop transplant dates (2 PRE fb 2 POST(T)), 4) one banded PRE fb two targeted POST following bed formation and targeted transplant dates (1 PRE fb 2 POST(T)), and 5) two targeted POST applications following bed formation and targeted transplant date with no PRE (2 POST(T)). The PRE herbicide was flumioxazin (211 g ai ha^{-1}), and the POST herbicides were a tank-mix of carfentrazone-ethyl (14 g ai ha^{-1}) for broadleaf control, clethodim (260 g ai ha^{-1}) for grass control, and halosulfuron-methyl (53 g ai ha^{-1}) for nutsedge control. We recognize that halosulfuron is a soil residual herbicide, but it is primarily used in row middles for POST control of nutsedge species and select broadleaf weeds. No surfactants were used in this experiment. The 2 banded PRE fb 2 banded POST treatment and the 2 banded PRE fb 2 targeted POST only differ in the application method and allow a comparison of banded versus targeted herbicide application technology following two PRE applications. The 1 banded PRE fb 2 targeted POST enables a comparison of targeted application technology following one less PRE herbicide than the previous two treatments. The 2 targeted POST (2 POST(T) treatment allows us to evaluate the same POST herbicides without a PRE application.

Experiment 1 was repeated 3 times. For Spring 2020, herbicides were applied on February 24, 2020, and March 11, 2020. In Fall 2020 (iteration 2), herbicides were applied on

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November 02, 2020, and November 16, 2020. On the third iteration of Experiment 1 (Spring 2021), herbicides were applied on March 11 and 31, 2021, respectively (Table 3).

Banded and targeted POST-glufosinate applications following banded PRE tank mixes of flumioxazin and *S*-metolachlor (Experiment 2). The objectives of this experiment were to evaluate glufosinate as a row middle herbicide within an overall herbicide program when applied using banded or targeted technology. Glufosinate was assessed with 0, 1, or 2 banded PRE applications of a tank mix of flumioxazin plus *S*-metolachlor. Treatments (Table 2) included 1) non-treated control, 2) banded PRE and banded POST applications following Bed formation and at the anticipated transplant date (2 PRE fb 2 POST (B)), 3) banded PRE applications following bed formation and at the anticipated transplant date fb targeted POST applications on the same dates (2 PRE fb 2 POST (T)), 4) one banded PRE and POST application following bed formation (1 PRE + 1 POST (B)), 5) one banded PRE application fb two targeted POST applications with one after bed formation and one at the expected transplant date (1 PRE fb 2 POST(T)), 6) one banded PRE application fb one banded POST after bed formation and one targeted POST at the expected transplant date (1 PRE fb 1 POST (B) fb 1 POST(T)), 7) one banded PRE fb one targeted POST after bed formation (PRE fb POST(T)), 8) two targeted POST applications (2 POST(T)) with the first following bed formation and the second at the expected transplant date, and 9) two banded POST applications (2 POST (B)) with the first following bed formation and the second at the expected transplant date. The treatments were selected to offer a comparison of 1 or 2 banded or targeted POST glufosinate applications following 0, 1, or 2 PRE herbicide applications. The PRE herbicide was flumioxazin (211 g ai ha^{-1}) tank mixed with *S*-metolachlor (937g ai ha^{-1}). The POST herbicide for Spring 2020 was paraquat dichloride (157 g ai ha^{-1}). Due to the known presence of paraquat-resistant goosegrass, in Fall 2020 and Spring 2021, the POST herbicide was switched to glufosinate-ammonium (450 g ai ha^{-1}). No surfactants were used in this experiment.

Experiment 2 was also repeated three times. For Spring 2020, the herbicide was applied on February 24, 2020, and March 11, 2020, after bed formation and at transplant time, respectively. In the Fall of 2020 (iteration 2), herbicides were applied on September 9, 2020, and October 29, 2020. In the third and final iteration of Experiment 1 (Spring 2021), the herbicides were applied on March 12 and 31, 2021, respectively (Table 3).

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Data collection

Data collection included weed density before and after treatments, herbicide usage, and herbicide costs (Table 3). The number of weeds in each plot was counted using two randomly placed permanent quadrats during the whole season, each 0.79 m^2. Each date's counts were done by category (broadleaf, grass, and nutsedge). Herbicide usage for each plot was calculated by subtracting the remaining volume of liquid in the spray bottles (2 L plastic bottles) immediately following application from the known volume needed for the treated area. The volume applied in each plot was then used to calculate the grams of active ingredient utilized for each treatment. The cost per treatment was calculated based on herbicide prices provided by local vendors in Central Florida for the year the experiment occurred. Differences in cost only reflect differences in herbicide usage and do not consider additional expenses such as equipment and labor.

Data analysis

Data were analyzed using the Mixed procedure in SAS (version 9.4; SAS Institute, Cary, NC). Block was considered a random variable, and herbicide treatments were a fixed variable. Experimental runs were analyzed separately as data collection occurred on different dates. Data assumptions were checked for normality and constant variance before analysis. Treatment means were separated using the least squares means statement in SAS with the post-hoc Tukey adjustment at $\alpha = 0.05$.

Results and Discussion

Banded and targeted mixed POST herbicide applications with 0, 1, or 2 PRE flumioxazin applications (Experiment 1).

Two targeted POST (carfentrazone + clethodim + halosulfuron) applications were as effective as two banded applications in the presence of PRE flumioxazin in Fall 2020 and Spring 2021 (Table 4). Targeted and banded methods lowered the total weed density by 96% 14 days after transplant (DATr) (Table 4). One application of PRE flumioxazin instead of two did not result in higher weed density. Two targeted POST-herbicide applications in the absence of flumioxazin lowered the weed density by 50 and 78% in the Fall 2020 and Spring 2021, respectively. All

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weed control programs reduced broadleaf and nutsedge density. However, broadleaf density tended to be higher without PRE flumioxazin, especially in the Fall. No consistent effect on grasses was observed, possibly due to the low population.

When applying two applications of PRE flumioxazin, the amount of active ingredient used in targeted applications versus banded applications decreased by 31, 20, and 23% following Bed formation in Spring 2020, Fall 2020, and Spring 2021, respectively (Table 5). The reduction in active ingredients when applied at transplant was 10, 29, and 14% in Spring 2020, Fall 2020, and Spring 2021, respectively. Reductions in herbicide use through targeted application methods led to a significant decrease in input costs, ranging from 37% to 51%, compared to the banded method. Applying one PRE flumioxazin application followed by two targeted POST applications resulted in savings ranging from 34% to 50%. However, the one flumioxazin application followed by two targeted carfentrazone + halosulfuron + clethodim applications did not have significantly lower costs when compared to the two PRE flumioxazin applications followed by two targeted POST applications—the lack of difference results from increased POST herbicide usage with only one PRE herbicide application. The relative costs of the PRE and POST herbicides must be considered when selecting the most cost-effective herbicide combination with smart spray technology. PRE herbicides tend to lower weed densities and reduce the use of POST herbicides when using targeted technology (Buzanini et al. 2024). However, if the cost of the POST active ingredient is low, there may be less incentive to apply PRE herbicides. Herbicide resistance management may be an additional consideration, as the use of both PRE and POST herbicides can slow the resistance evolution (Somerville et al. 2017) and, at the same time, maximize the benefits achieved with targeted spray technology.

It is important to note that two targeted POST herbicide applications without flumioxazin used 82% more active ingredients than the treatment with two PRE herbicide applications. However, in Fall 2020, the total average weed density that persisted in this treatment was not significantly different from the nontreated control. This highlights the importance of using PRE herbicides, even though they may incur additional costs. The findings of this study are consistent with the reports by Buzanini et al. (2024), where the application of flumioxazin led to a reduction in overall weed density. However, they also observed lower costs in treatments where a PRE-herbicide was used, as higher savings were observed from targeted glyphosate

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application. In the present study, the non-PRE-herbicide application led to lower costs, with a significant active ingredient reduction compared to PRE-herbicide treatments. The differences between the studies can be correlated with weed density and the POST-herbicides used.

Banded and targeted POST-glufosinate applications following banded PRE mixtures of flumioxazin and *S*-metolachlor (Experiment 2).

Herbicide treatments had no statistical effect on weed density at 14 days after bed formation (DABF) in Fall 2020 and Spring 2021 (Table 6). However, 14 DATr the 2 PRE herbicide (flumioxazin + S-metolachlor) applications with two targeted POST herbicide (glufosinate-ammonium) applications significantly reduced the total weed density by 98% and 89% compared to the non-treated control in Fall 2020 and Spring 2021, respectively. In the Fall of 2020, the nutsedge density observed in all treatments was significantly lower than the nontreated control 14 DABF; however, in Spring 2021, the treatments were not significantly different from the nontreated control. The nutsedge densities were also dramatically different between seasons.

For broadleaf weed density in both seasons, the two targeted glufosinate-ammonium applications were equivalent to the banded method in the presence of PRE-herbicide applications 14 DATr. There was no significant difference in broadleaf density following one or two PRE applications. In the absence of flumioxazin + *S*-metolachlor, the broadleaf density was not significantly different from the nontreated control. Combining S-metolachlor and flumioxazin in a tank mix is more effective than using *S*-metolachlor alone. Incorporating flumioxazin into the tank mix can improve weed control as it provides some localized POST control on broadleaf weeds, which may be adequate to kill small weeds that may have emerged before PRE-herbicide applications (Clewis et al. 2007; Boyd 2016).

Two flumioxazin + S-metolachlor applications associated with two targeted glufosinate-ammonium applications lowered herbicide costs by 11 by 13% and decreased the herbicide costs by 9% compared to the banded method (Table 7). One PRE application at bed formation plus two targeted POST herbicide applications reduced the final herbicide costs by an average of 51% compared to two PRE applications and two POST banded applications. Two targeted glufosinate-ammonium applications with no flumioxazin + *S*-metolachlor applied lowered the

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total cost by 55% compared to the banded method by significantly reducing the amount of active ingredient applied by 40 to 53%. The application of one PRE herbicide, followed by two targeted POST herbicide applications, did not significantly reduce the amount of active ingredient or the total costs compared to using one PRE herbicide and one banded POST herbicide application at bed formation, along with one targeted application at transplant.

The amount of herbicide and number of active ingredients needed can vary based on a few factors, such as the type of weeds, their growth stage, weed density, weather during spraying, and if any weeds present are resistant to the herbicide (Dammer and Wartenberg 2007). Gutjarh and Gehards (2010) found that using a GPS-guided sprayer resulted in herbicide savings of up to 90% for grass weeds in winter cereals, 78% in maize, and 36% in sugar beet. Using a prototype variable rate sprayer, Esau et al. (2014) observed 51% herbicide savings on wild blueberry fields. Buzanini et al. (2023) reported that using smart spray technology can reduce the POST herbicide volume application by 26 to 42% in jalapeno pepper (*Capsicum annuum*) plasticulture fields without a PRE herbicide application.

Based on these findings, it is concluded that the smart spray system is an effective technology for selectively applying herbicides only where needed, and this technology has the potential to reduce herbicide usage. PRE herbicides increased overall herbicide costs but tended to lower weed densities. Utilizing a tank mix of flumioxazin + *S*-metolachlor can play a crucial role in the initial management of weeds and enhance the efficacy of subsequent targeted POST herbicide applications.

Practical Implications

Targeted weed control systems that use artificial intelligence for weed detection and identification effectively reduce herbicide inputs, herbicide costs, crop damage, labor, and risks. The system presented in this paper detected and localized weeds and reduced herbicide usage compared to conventional techniques. Targeted POST herbicide applications should be used with PRE herbicides to optimize cost reductions and weed control. The absence of PRE herbicides can reduce herbicide costs compared to using two PRE applications, but weed density may be higher and POST herbicide savings lower. This study was done based on real-world field trials following commercial standards, and we are therefore confident that similar results would be obtained on commercial farms.

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Conflicts of interest

No competing interests have been declared.

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Table 1. Herbicide product, application rate, and manufacturer information

Experiment	Common name	Trade name	Rate	Manufacturer
			g ai ha^{-1}	
1	Carfentrazone	Aim®	14	FMC Corporation, Philadelphia PA 19104
	Flumioxazin	Chateau®	211	Valent U.S.A. LLC P.O. Box 8025 Walnut Creek CA 94596-8025
	Clethodim	Select®	260	Winfield Solutions, LLC St. Paul, MN 55164
	Halosulfuron-methyl	Sandea®	53	Gowan Company, Yuma, Arizona 85364
2	*S*-metolachlor	Dual Magnum®	937.4	Syngenta Crop Protection, LLC P. O. Box 18300 Greensboro, North Carolina 27419-8300
	Flumioxazin	Chateau®	211	Valent U.S.A. LLC P.O. Box 8025 Walnut Creek CA 94596-8025
	Paraquat dichloride	Gramoxone® SL 2.0	157	Syngenta Crop Protection, LLC P. O. Box 18300 Greensboro, North Carolina 27419-8300
	Glufosinate-ammonium	Rely®	450	Bayer Crop Science LP, NC 27709

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Table 2. Herbicide programs evaluated for row middles in plasticulture vegetable production systems at Wimauma, FL, in 2020 and 2021.

		Following Bed Formation		At Transplant	
Experiment	Treatment	Banded	Targeted	Banded	Targeted
	Non-treated control	----	----	----	----
	2[b]PRE fb 2POST (B)	Flum+Carf+Clet+Halo	----	Flum+ Carf + Clet +Halo	----
1	2PRE fb 2POST (T)	Flum	Carf+ Clet +Halo	Flum	Carf + Clet +Halo
	1[b]PRE fb 2POST (T)	Flum	Carf + Clet +Halo	----	Carf + Clet +Halo
	2POST (T)	----		----	
	Non-treated control	----	----	----	----
	2 PRE fb 2 POST (B)	Flum+ S-met +Gluf[a]	----	Flum+ S-met +Gluf	----
	2 PRE fb 2 POST (T)	Flum+S-met	Gluf	Flum+ S-met	Gluf
	PRE + POST (B)	Flum+S-met+Gluf	----	----	---
2	PRE fb 2 POST (T)	Flum+S-met	Gluf	----	Gluf
	PRE fb POST (B) fb POST (T)	Flum+ S-met	Gluf	Gluf	----
	PRE fb POST (T)	Flum+ S-met	Gluf	----	----
	2 POST (T)	----	Gluf	----	Gluf
	2 POST (B)	Gluf	----	Gluf	---

Abbreviation: PRE = preemergence application; POST = postemergence application; B = banded; T = targeted; fb = followed by; '+'- tank-mixes; Flum = Flumioxazin, Carf = Carfentrazone, Clet = Clethodim; Halo = Halosulfuron-methyl; S-met = *S*-metolachlor; Gluf = Glufosinate-ammonium

[a]The paraquat dichloride was not included in this table since no data from the Spring of 2020 was included in the following analysis.

[b] 2 – two successive applications; 1 – one application only (within 14 days of bed formation)

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Table 3. Data collection dates for each experiment and iteration at Wimauma, FL, in 2020 and 2021.

Experiment	Iteration	Application Dates	Weed density
1	Spring 20	February 24, 2020	---
		March 11, 2020	---
	Fall 20	September 09, 2020	November 30, 2020
		October 29, 2020	December 15, 2020
	Spring 21	March 12, 2021	March 26, 2021
		March 31, 2020	April 09, 2021
2	Spring 20	February 24, 2020	---
		March 11, 2020	---
	Fall 20	September 09, 2020	September 22, 2020
		October 29, 2020	November 12, 2020
	Spring 21	March 12, 2021	March 26, 2021
		March 31, 2020	April 09, 2021

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Table 4. The effect of herbicides on weed density when applications are banded or targeted in row middles in Experiment 1, in Wimauma, FL.

Trial	Treatments	Broadleaf				Grass			Nutsedge				Total[d]		
		14 DABF		14 DATr		14 DABF		14 DATr	14 DABF		14 DATr		14 DABF	14 DATr	
		---weed m^{-2}--													
Fall 20	Non-treated control	26	a[e]	27	a	1	ab	1	3	a	3	a	23	24	a
	2[c]PRE[a] fb 2POST[b] (B)	6	b	1	b	0	b	0	1	ab	0	b	7	1	b
	2PRE fb 2POST (T)	2	b	1	b	1	ab	0	0	b	0	b	3	1	b
	1[c]PRE fb 2POST (T)	13	ab	1	b	0	b	1	1	ab	1	ab	13	2	ab
	2POST (T)	23	a	10	ab	10	a	1	1	ab	1	ab	29	12	ab
	P value	0.0037		0.0032		0.0165		0.4222	0.0273		0.0028		0.3379	0.0046	
Spring 21	Non-treated control	41	a	34	a	40	a	25 a	49	a	40	a	97	74	a
	2PRE fb 2POST (B)	2	b	1	b	7	ab	0 b	4	b	0	b	12	1	c
	2PRE fb 2POST (T)	3	b	0	b	16	ab	0 b	6	b	1	b	22	1	c
	1PRE fb 2POST (T)	2	b	3	b	1	b	3 b	21	ab	4	b	23	9	bc
	2POST (T)	7	b	11	b	8 ab	ab	2 b	11	b	3	b	22	16	ab
	P value	0.0027		<0.001		0.0373		0.0015	0.0142		<0.0001		0.1399	0.005	

Abbreviation: PRE- preemergence application; POST- postemergence application; B- banded; T- targeted; fb- followed by; '+'- tank-mixes

[a]PRE-herbicide applied: Flumioxazin (211 g ai ha^{-1})

[b] POST-herbicides applied: Carfentrazone (14 g ai ha^{-1}) + Clethodim (260 g ai ha^{-1}) + Halosulfuron-methyl (53 g ai ha^{-1})

[c] 2 – two successive applications; 1 – one application only (at pre-transplant time)

[d] Total average of density between all weed classes and evaluation dates.

[e] Means within a column followed by the same letter are not significantly different according to Tukey test (a = 0.05)

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Table 5. The costs and amount of active ingredient used when applying varying herbicide programs in row middles with banded and targeted technologies for Experiment 1, in Wimauma, FL.

		Bed Formation					Transplant					Total[d]		
		Method					Method							
Trial	Treatments	Banded	Targeted	Total		Cost	Banded	Targeted	Total		Cost	Active ingredient		Cost
		--------------g ai ha^{-1}--------------				\$ ha^{-1}	--------------g ai ha^{-1}--------------				\$ ha^{-1}	g ai ha^{-1}		\$ ha^{-1}
Spring 20	Non-treated control	---	---	---		---	---	---	---		---	---		---
	2[c]PRE[a] fb1 2POST [b](B)	259.5	---	259.5	a[e]	187	259.5	---	259.5	a	144	519	a	331
	2PRE fb2 2POST (T)	170	9.5	179.5	a	62	170	63.6	233.6	ab	104	413.1	b	209
	1[c]PRE fb3 2POST (T)	170	5.9	175.9	a	54	170	76.3	246.3	ab	124	422.2	b	220
	2POST (T)	---	13	13	b	20	---	75.7	75.7	b	118	88.7	c	138
	P value			0.0009					<0.001			<0.0001		
Fall 20	Non-treated control	---	---	---		---	---	---	---		---	---		---
	2PRE fb1 2POST (B)	394.6	---	394.6	a	318	106.5	---	394.6	a	318	789.2	a	636
	2PRE fb2 2POST (T)	226.7	90.7	317.3	b	185	226.7	52.4	279.1	b	127	596.4	b	312
	1PRE fb3 2POST (T)	226.7	98.3	325	b	194	226.7	108.8	335.5	b	212	660.5	b	406

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	2POST (T)	---	63.8	63.8	c	97	---	105.1	105.1	c	159	168.9	c	256
	P value			<0.0001					<0.0001			<0.0001		
Spring 21	Non-treated control	---	---	---		---	---	---	---		---	---		---
	2PRE fb1 2POST (B)	411.2	---	411.2	a	317	411.6	---	411.6	a	318	822.8	a	635
	2PRE fb2 2POST (T)	255	63.1	318.1	a	138	255	99.5	354.5	a	204	672.6	b	342
	1PRE fb3 2POST (T)	255	49.1	304.1	a	115	255	100.1	355.1	a	205	659.2	b	320
	2POST (T)	---	46.2	46.2	b	66	---	84.9	84.9	b	133	131.1	c	199
	P value			<0.0001					<0.0001			<0.0001		

Abbreviation: PRE- preemergence application; POST- postemergence application; B- banded; T- targeted; fb- followed by; '+'- tank-mixes

[a]PRE-herbicide applied: Flumioxazin (211 g ai ha^{-1})

[b] POST-herbicides applied: Carfentrazone (14 g ai ha^{-1}) + Clethodim (260 g ai ha^{-1}) + Halosulfuron-methyl (53 g ai ha^{-1})

[c] 2 – two successive applications; 1 – one application only (at pre-transplant time)

[d] Total active ingredient applied and cost over two application times.

[e]Means within a column followed by the same letter are not significantly different according to Tukey test (a = 0.05)

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Table 6. The effect of herbicides on weed density when applied with a banded or targeted applicator in row middles in Experiment 2, in Wimauma, FL.

Trial	Treatments	Broadleaf			Grass		Nutsedge			Total		
		14 DABF	14 DATr		14 DABF	14 DATr	14 DABF	14 DATr		14 DABF[d]	14 DATr	
		------weed m^{-2}------										
Fall 20	Non-treated control	13	99	a[e]	23	4	2	21	a	32	89	a
	2[c] PRE[a] fb 2 POST[b] (B)	2	36	ab	19	1	0	0	b	10	37	ab
	2 PRE fb 2 POST (T)	0	2	b	17	0	0	0	b	13	2	b
	PRE + POST (B)	1	7	b	3	1	0	2	b	3	8	b
	PRE fb 2 POST (T)	2	28	ab	9	1	0	0	b	11	15	b
	PRE fb POST (B) fb POST (T)	6	46	ab	15	2	0	1	b	16	37	ab
	PRE fb POST (T)	1	1	b	2	0	0	0	b	3	1	b
	2 POST (T)	4.5	10	b	4	3	0	0	b	8	11	b
	2 POST (B)	8	27	ab	17	0	1	0	b	22	21	ab
	P-value	0.0913	0.0106		0.0801	0.5746	0.4334	0.0234		0.0431	0.0082	
Spring	Non-treated control	74	29	a	68	35	69	37		158	91	a

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2 PRE fb 2 POST (B)	10	1	b	48	18	58	9	87	26	ab
2 PRE fb 2 POST (T)	8	0	b	20	2	15	8	32	10	b
PRE + POST (B)	1	4	b	8	18	67	27	57	42	ab
PRE fb 2 POST (T)	8	2	b	67	19	48	8	123	27	ab
PRE fb POST (B) fb POST (T)	9	2	b	56	21	72	23	117	39	ab
PRE fb POST (T)	14	9	ab	11	12	27	10	51	32	ab
2 POST (T)	31	12	ab	56	16	91	37	178	65	ab
2 POST (B)	50	17	ab	57	31	60	24	98	56	ab
P-value	0.0874	0.0009		0.387	0.3403	0.7466	0.0575	0.5057	0.0324	

Abbreviation: PRE- preemergence application; POST- postemergence application; B- banded; T- targeted; fb- followed by; '+'- tank-mixes

[a]PRE-herbicide applied: Flumioxazin (211 g ai ha^{-1}) + S-metolachlor (937.4 g ai ha^{-1})

[b] POST-herbicides applied: Glufosinate ammonium (133 g ai ha^{-1})

[c] 2 – two successive applications; 1 – one application only (at pre-transplant time)

[d] Total density between all weed classes and evaluation dates.

[e] Means within a column followed by the same letter are not significantly different according to Tukey test (a = 0.05)

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Table 7. The costs and amount of active ingredient used when applying varying herbicide programs in row middles with banded and targeted technologies for Experiment 2, in Wimauma, FL.

		Bed Formation					Transplant							
		Method					Method					Total[d]		
Trial	Treatments	Banded	Targeted	Total		Cost	Banded	Targeted	Total		Cost	Active ingredient		Cost
		--------------g ai ha^{-1}--------------				$ ha^{-1}	--------------g ai ha^{-1}--------------				$ ha^{-1}	g ai ha^{-1}		$ ha^{-1}
Spring 20	Non-treated control	---	---	---		---	---	---	---		---	---		---
	2[c]PRE[a] fb 2 POST[b] (B)	1117.9	---	1117.9	a[e]	65	1117.9	---	1117.9	a	65	2235.8	a	130
	2 PRE fb 2 POST (T)	858.1	209.8	1067.9	b	63	858.1	12	870.1	b	63	1937.9	b	126
	PRE + POST (B)	1117.9	---	1117.9	a	65	---	---	---		---	1117.9	d	65
	PRE fb 2 POST (T)	858.1	212.4	1070.5	b	63	---	72	72.4	d	3.1	1142.2	d	66
	PRE fb POST (B) fb POST (T)	858.1	210.2	1068.3	b	63	259.8	---	259.8	c	11	1328.5	c	74
	PRE fb POST (T)	858.1	215.3	1073.4	b	63	---	---	---		---	1073.4	e	63
	2 POST (T)	---	208.7	208.7	d	9	---	39	39.3	d	1.7	245.9	g	10
	2 POST (B)	259.8	---	259.8	c	11	259.8	---	259.8	c	11	519.6	f	22
	P-value	---	---	<0.0001		---	---	---	<0.0001		---	<0.0001		---
Fall 20	Non-treated control	---	---	---		---	---	---	---		---	---		---
	2 PRE fb 2	1117.9	0	1117.	a	65	1227.1	0	1227.	a	93	2345	a	158

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	POST (B)			9					1				
	2 PRE fb 2 POST (T)	858.1	107.2	965.3	ab	59	914	124	1037.7	b	78	2002.9	b	136
	PRE + POST (B)	111.9	0	1117.9	a	65	---	---	---		---	1117.9	d	65
	PRE fb 2 POST (T)	858.1	150.1	1008.2	ab	60	---	77	77	d	8	1085.2	de	68
	PRE fb POST (B) fb POST (T)	858.1	120.5	1033.2	ab	57	313.1	---	313.1	c	25	1346.3	c	83
	PRE fb POST (T)	858.1	89.1	947.2	b	40	---	---	---			946.7	e	40
	2 POST (T)	0	104.5	104.5	d	1	---	84	83.9	d	9	188.4	g	10
	2 POST (B)	259.8	0	259.8	c	11	313.1	---	313.1	c	25	572.9	f	36
	P-value	---	---	<0.0001		---	---	---	<0.0001		---	<0.0001		---
Spring 21	Non-treated control	---	---	---		---	---	---	---		---	---		---
	2 PRE fb 2 POST (B)	1227.1	0	1227.1	a	93	1227.1	0	1227.1	a	93	2454.2	a	186
	2 PRE fb 2 POST (T)	914	214.2	1128.2	ab	85	914	153.3	1067.3	b	80	2195.5	b	165
	PRE + POST (B)	1227.1	---	1227.1	a	93	---	---	---		---	1227.1	cd	93
	PRE fb 2 POST (T)	914	199.4	1113.4	ab	84	--	124.2	124.2	d	10	1237.6	cd	94
	PRE fb POST (B) fb POST (T)	914	143.9	1057.9	b	79	313.1	---	313.1	c	68	1371	c	147
	PRE fb POST (T)	914	201.3	1115.3	ab	84	---	---	---		---	1115.3	d	84
	2 POST (T)	---	192.8	192.8	c	16	---	185.5	185.5	d	15	378.3	f	31

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2 POST (B)	313.1	---	313.1	c	25	313.1	---	313.1	c	25	626.2	e	51
P-value	---	---	<0.0001		---	---	---	<0.0001		---	<0.0001		---

Abbreviation: PRE- preemergence application; POST- postemergence application; B- banded; T- targeted; fb- followed by; ‘+’- tank-mixes

[a]PRE-herbicide applied: Flumioxazin (211 g ai ha^{-1}) + S-metolachlor (937.4 g ai ha^{-1})

[b] POST-herbicides applied: Glufosinate ammonium (133 g ai ha^{-1})

[c] 2 – two successive applications.

[d] Total active ingredient applied and cost over two application times.

[e] Means within a column followed by the same letter are not significantly different according to Tukey test (a = 0.05)

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